Nantucket nub scallops, *Argopecten irradians*, overwinter twice and spawn for the first time at 21 - 22 months of age

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Running title: *Argopecten irradians* overwinter twice and spawn

ABSTRACT

Nub bay scallops, *Argopecten irradians* (Lamarck, 1819) are bay scallops from a fall set that subsequently develop an annual growth line between 1 and 20 mm from the umbo in the early spring.. Over 80 % of nub scallops survive their second winter to spawn, generally for the first time at 21- 22 months of age. Nub scallops develop a second well-defined growth line after their second winter. Over 35 % of second year nubs live to the commercial harvest season, entering their third year of life, compared to most classic bay scallops (summer set) that do not attain this age.

KEY WORDS: nub scallop, bay scallop, *Argopecten irradians*, overwinter, spawn, reproduction.

INTRODUCTION

Adult bay scallops, *Argopecten irradians* (Lamarck, 1819), typically form a well-defined growth ring, 30 - 50 mm from the umbo, indicating that they have over-wintered (Belding, 1910; Gutsell, 1930; Sastry, 1966). MacFarlane, however, documented that 9% of the bay scallops in her 1979 survey in Pleasant Bay, Massachusetts had a growth line at 4-8 mm from the umbo and classified these scallops as “ring at hinge” (MacFarlane, 1991). On Nantucket Island, the “ring at hinge” scallops are called “nub scallops” and are defined as bay scallops possessing a growth ring positioned between 1 and 20 mm from the umbo. During some years on Nantucket, nub scallops have composed up to eighty percent of the scallop population (Shellfish Wardens, personal communication).

The small growth line on the nub scallop indicates that these scallops were a result of fall spawn rather than the more typical summer spawn (Sastry, 1966). Shell cessation occurs when the water temperature decreases to ~7.2 ^{o}C (Fay et al. 1983), usually occurring in October. The late born seed have a limited growing season this first year. The growth line is formed when the shell begins to accrete after the winter period of cessation. The position of the growth line on the shell is a result of the length of time the scallop had to accrete shell before the water temperature dropped to ~7. 2 ^{o}C. Nub scallops over-winter at 1 - 20 mm in size, whereas classic, or summer spawned, scallops over-winter at 31 – 41 mm in size (Belding, 1910). Sastry (1966) found that bay scallops spawn when they are at least 12 months of age and when there is a rapid rise or fall in water temperature around 20 - 22.2 ^{o}C. In Nantucket Harbor, these temperature changes occur first in June or July and again in September or October (**Figure 1**) thus initiating a summer and a fall spawning maxima, with some prolonged spawning throughout the summer-fall period during some years.

Depending on environmental conditions in the harbor (water temperature, phytoplankton levels, etc), the nub scallop may or may not reach sexual maturity during its first summer-fall spawning window (**Figure 2**). If any scallop is less than 12 months of age during its first spawning window, it likely will not spawn (Sastry, 1966). Scallops with growth lines less than 20 mm in size at the time of the fall spawning window do not spawn (Conant 2002). We hypothesize that these year old nub scallops that do not spawn for the first time in the fall spawning window will over-winter a second time and spawn in June or July at 20 or 21 months of age. The goal of this study is to determine whether nub scallops 1) survive their second winter, 2) establish a second well-defined growth ring after this second winter, and 3) spawn during the following summer at 20 to 21 months of age.

METHODS AND MATERIALS

Six hundred 16 to 17 month-old nub scallops (65 mm to 70 mm in length, with a single growth ring between 5 mm and 20 mm from the umbo) were collected during December 2000 and held in an upweller located inside the Brant Point Marine Facility, Nantucket, MA. A continuous flow of seawater was established by drawing seawater through a pipe located at the top of the holding bin. Raw seawater was replenished through the bottom mesh in the holding bin as a result of the vacuum action. This pumping system provided a continual circulation of raw seawater inside the upweller. A control group of four hundred 7 month-old juvenile (classic) scallops (40 - 60 mm in length, with no growth ring) were similarly collected and held.

In January 2001, nub scallops were transferred to 4’ x 4’ x 3’cages made of 1 inch wire mesh. Each cage contained a total of eight trays, four on a side, accessed through a front door. Two four foot lengths of six inch plastic corrugated piping held the cages above the mud/sand bottom. The scallops were held in 3’x 1.5’ rigid plastic bags of ¼” mesh. Nub scallops were divided up into three cages (stocking density 25 scallops per bag) and transferred to three sites in Nantucket Harbor in 1.3 m to 5.3 m of water (**Figure 3**). All four hundred of the control juvenile scallops were caged (stocking density 50 scallops per bag, due to their smaller size) and transferred to a single site in Nantucket Harbor in 2.6 m of water.

Caged scallops were monitored each month between March and November for mortality, gonad maturation and spawning evidence. During each visit, the cage was brought out of the water and opened. Each bag was removed, examined and cleaned. The living, dead, and “slipped hinged” scallops (i.e. scallops with a broken external ligament) were counted and recorded. Both dead and “slipped hinged” scallops were removed and counted as dead. Observations were made on the physical condition of the scallops as well as the presence of any invasive or encrusting organisms. The healthy animals were returned to the bags, and the cages were placed back into the water. The whole inspection and counting time was kept to less than 30 minutes per cage to minimize the impact to the scallops.

Sexual stages were determined by inspection of the gonads for each of seven stages of development, determined by coloration (Sastry, 1963). Stage 1 scallops had small transparent gonads with primary germ cells in the follicles. In Stage 2, the gonad was larger and translucent but the testes were not distinguishable from ovaries in gross examination. Black epithelial cells covered the gonad. In Stage 3, the gonad expanded and epithelial cells were light grey. The gonad began to differentiate, as indicated by the presence of a white line between the ventral orange egg section in the gonad, and the black dorsal edge containing sperm (Belding, 1910). In Stage 4, the gonad exhibited a bright orange ovary and cream-colored testes. Microscopic examination showed active spermatozoa and mature pear-shaped oocytes (Sastry, 1963). These scallops were sexually mature and ready to spawn. Stage 5 scallops were partially spent as indicated by a deflated gonad, mostly cream in color with a light orange section still visible. In Stage 6, the gonad is completely spent and gonad is beige, with no differentiation between testicular and ovarian regions (Sastry 1963). Stage 7, the gonads were partially regenerating, as the black epithelial cells began to build and cover the gonad.

RESULTS

Fouling

The cages reduced water circulation permitting several species of sponges, tunicates, barnacle, crabs, fish, and shellfish to settle in the cages and bags. The relative abundance of each fouling species was not recorded. Fouling of cages and bags was first observed on April 31st, and extended throughout the duration of the experiment. Bay barnacles (*Balanus improvisus* (Darwin, 1854)) and Northern Rock Barnacles (*Balanus balanoides* (L., 1767)) were commonly observed on all scallop surfaces, cages, and bags beginning on April 31st but were not removed during the periodic inspection of the cage. Encrusting sponge (*Halichondria panicea* (Pallas, 1766), Crumb of Bread) and (*Microciona proliera* (Ellis and Solander, 1786), Red Beard Sponge) were also common to all cages, but the majority of sponges were removed at each site visit. Red Beard Sponge was first observed in June attached to several scallops in cage 4. Encrusting sponge increased in concentration as the experiment progressed covering scallops, bags, and cages. Nipple Sponge (*Polymastia robusta* (Bowerbank, 1860)) was first observed on bags in cage 2 on July 3rd and was present in all nub scallop cages by

September. Nipple Sponge was absent in the control cage.

Although cages 1 (control) and 4 (nub scallops) were located in the same area and depth, only Spider crabs (*Libinia emarginata* (Leach, 1815)), Green crabs (*Carcinus maenas* (L., 1758)), and Cunner fish (*Tautogolabrus adspersus* (Walbaum, 1792)) were common to both cages. All fish and crab species were removed during each site visit. Blue crab (*Callinectes sapidus* (Rathbun, 1895)), tautog (*Tautogs onitis* (L., 1758)), Northern Searobin (*Prionotus carolinus* (L., 1771)), Oyster drills (*Urosalpinx cinerea* (Say, 1822)) and blue mussels (*Mytilus edulis* (L., 1758)) were unique to the cage 1 (control). Eastern White Slipper Snails (*Crepidula plana* (Say, 1822)) and Orange Sea Grapes (*Molgula citrina* (Alder and Hancock, 1848)) were limited to cages 2 and 4. Easter White Slipper Snails were not removed from the surfaces of the scallops. Golden Star tunicates (*Boytryllus schlosseri* (Pallas, 1766)) were common to cages 2 and 3, while Club tunicates (*Styela clava* (Herdman, 1881)) were unique to cage 2.

Mortality

The control group had an average mortality rate of 1.5% per month between March and June. Mortality increased to 2.5% per month during July and August as the gonad ripened. Total mortality prior to the spawning event was 9.5%. Spawning accounted for an additional 1.8% mortality between August and September. At the end of the experiment, in December, total mortality was 13.5%.

Mortality rates for nub scallops increased throughout the study with the highest rates of mortality occurring after spawning in August through October.   Although the scallops continued to grow, their hinges weakened and their shells became brittle. Nub scallops in cage 2 had the greatest mortality rates, averaging 5% per month between March and July. Total mortality reached 20.5% in July prior to spawning. Spawning accounted for an additional 18.5% mortality during July and August. The greatest mortality was recorded between August and November where an additional 37.5% scallops died after the spawning period. Total mortality for nub scallops in cage 2 was 76.5%.

In cage 3, located in 1.3 m of water, two bags containing nub scallops froze in the ice in February and all fifty nub scallops in those bags died. Ignoring this initial loss of scallops, the mortality rate of the remaining nub scallops in cage 3 was similar to the other cages (**Figure 4**).

Nub scallops in cage 4 had similar mortality rates as those in cage 3 between March and early July averaging 3% per month. Spawning accounted for 16.5% mortality in cage 3 and 22.5% mortality in cage 4. Post-spawning accounted for an additional 22% mortality in cage 3 and an additional 20% mortality in cage 4. Cages 3 and 4 followed similar mortality trends through November. The total mortality for cage 3 was 78.5% and cage 4 was 58.5%.

Overall the nub scallops had an average mortality rate of 3% per month and the control scallops 1.5% per month between March and July. Spawning accounted for an average mortality of 19.1% of the nub scallops and 1.8% of the control group. The greatest mortality occurred as the gonad ripened, during spawning and after the spawning event.

Cumulative Survival

The nub scallop had a lower survival rate (87.5%) than the classic scallop (99.2%) during the first three months of the transplant (**Table 1**). This lower cumulative survival rate of the nub scallops was largely due to the loss of fifty animals killed by the ice. Ignoring the initial loss in cage 3, the survival rate of the nub scallops was improved to 93.6%.

Nub adults in cages 2, 3, and 4 had similar survival rate trends (Figure 5). On average, 81% of the nub scallops survived their second winter to enter their first spawning window as mature adults in June at 21 months of age. On average, 60.2% of nub scallops survived the post-spawning period to reach 23 months of age, as compared to 88.7% of the control, which reached 15 months of age. At least 37.5% of the nub scallops (26 months of age) and 86.5% of the control scallops (18 months of age) survived to be a harvestable age at the beginning of the commercial scallop season in November.

Growth line and age

Following the January transplant, growth did not resume until early spring. One millimeter of shell growth was first observed on April 31st when water temperatures ranged from 11.7 ^{o}C to 12 ^{o}C. One hundred percent of the scallops in cage 1 (control) developed their first well-defined growth line by June 25, 2001 at approximately 13 months of age. One hundred percent of nub scallops in cages 2 and 4 developed their second well-defined growth line by June 25, 2001 at approximately 23 months of age.

The control scallops had 25 mm of new shell growth on July 3rd, whereas nub scallops had only 4 mm of new shell growth by August 6th. Nub scallops in cage 3 had a slower growth rate than the other three cages but developed a second well-defined growth line by August at 25 months of age. In cage 3, a second well-defined growth line with 3 mm of new shell growth was visible on August 6th. The nub scallops' first growth line ranged from 3 mm to 20 mm as measured from the umbo. The nub scallops' second growth line was high on the shell and ranged from 60 mm to 72 mm measured from the umbo. The total shell height ranged from 65 mm to 75 mm for nub scallops. Data indicate that nub scallops grew at a slower rate than control scallops but all scallops developed a well-defined growth line.

Gonadal Development and Spawning

The nub scallops' gonads ripened more quickly than the control group and spawned first between July 3rd and August 6th (**Table 2**). The control group spawned between August 6th and September 12th, at least one month later than the nub scallops.

In April, the nub scallop gonad was in stage 2 and early stage 3. The gonads were larger and translucent, but the testes were not distinguishable from the ovaries. Some nub adult gonads had turned light grey. The control group's gonads were small and black, stage 1. In May, all nub gonads were stage 3 with a distinct white line separating the light orange section from the black dorsal edge while the control group remained stage 1. In June, the nub gonads were stage 4 and the control group had reached stage 2. In July, the nub adults were ready to spawn at late stage 4, while the control group was still at stage 3. The nub scallops spawned prior to the August site visit. On August 6th, the gonads of the nub scallops were partially and completely spent, stage 5 and stage 6, respectively. In cage 2, two nub scallops were at stage 7 where the gonads had already begun to regenerate. The control group was at stage 4 in August but had not spawned.

On September 12th, the nub scallops were stage 7 and the control group gonads were at stages 5 and 6. The control group had spawned prior to the September sample date. In cage 2, several nub adult scallops appeared to have spawned again in the fall based on color and condition of the gonad. With the exception of these scallops, nub scallops did not spawn a second time in the same year (fall 2001), although all the scallops had begun to regenerate their gonads. In December, the control group gonads reached stage 7.

Caged scallops spawned later than the wild population. Based on harbor water temperature data (Curley 2003) and shell size (Belding 1910), the wild classic adults (12 months) and the wild 2^{nd} year nub adults (21 months) spawned prior to June 19, 2001. The caged nub scallops spawned at 22 months of age at the end of July. On August 6, 2001 many of the bags in cage 2 contained up to 300 wild seed scallops ranging in size from 5 mm to 12 mm. Seed scallops, 25 mm in size, were also observed on the outside of these bags. On the same date in the control cage, two 10-15 mm seed were observed in one bag. Caged control scallops spawned between the August and September visits at 14 to 15 months of age.

DISCUSSION

Data from this 9-month transplant study clearly demonstrate that the majority of nub scallops are capable of over-wintering a second time at 15 to 18 months of age, producing a second raised growth line and successfully spawning at 21-22 months of age. After their first spawning period, over 35% of the experimental nub scallops lived to the following winter harvesting season, when they were over 2.5 years old.

There appeared to be a significant affect on survival rates due to localized conditions in the harbor. The best survival rates were observed in Cages 1 and 4, which were located at Pocomo West in 2.5 m of water. Pocomo West was located in the middle of the harbor and received relatively high water circulation. Cage 3 had the lowest survival rates and the slowest shell growth. Cage 3 was located in Second Bend, an area of high circulation near the entrance to Nantucket Harbor in 1.3 m of water. At this site, the depth of water may have been too shallow for successful over-wintering. Fouling caused reduced food availability for all the caged scallops retarding gonad maturation and shell growth. In particular, the red beard sponge was found to smother the scallops, either covering them completely, or weakening their hinges and directly resulting in their deaths. We noted that cage confinement resulted in a lack of activity and use of the external ligament, which caused the ligament to become brittle and break resulting in the “slipped-hinge” scallops. Slipped hinged scallops were removed and counted as dead. Spawning was believed to physically exhaust the scallops (Sastry, 1965). It appears that the sizable die off that occurs after a spawning event is the result of exhaustion, gill damage, or age.

Our findings indicate that there are four age classes of scallops that contribute to the reproductive success of the Nantucket bay scallop fishery (first year classic, second year classic, first year nub, second year nub). The spawning window in Nantucket Harbor typically begins in mid June and ends in late September. This window is composed of two spawning events corresponding to two water temperature changes one in the summer and one in the fall. At the time of the first spawning event in June, the second year nub adult (21 months), the second year classic adult (24 months), and, depending on the year, the classic first year adult (11-12 months) are available to spawn. At the time of the second spawning event in the fall, the first year classic adult (14 – 15 months), and, depending on the year, the first year nub adult (11 -12 months) and second year nub adult (24 months) are available to spawn. Spawning is a function of age, phytoplankton concentration, gonad maturation, and water temperature (Belding 1910 and Sastry 1963, 1966). Environmental conditions dictate the rate of gonad maturation. Water temperature and gonad maturation must be in synchrony for spawning to occur.

Nub adult scallops that do not spawn in their second fall at 11 to 12 months of age will absorb their eggs and sperm giving them a chance to spawn with greater fecundity during the next spawning event, provided that they have not been harvested or reached their maximum life expectancy (Sastry 1968). Based on this study in Nantucket Harbor, if the 15 month old nub adult scallops are not harvested during the commercial season, over 80% of them will live to spawn at 21 to 22 months of age. These older nub adult scallops have larger gonads at 21 months of age, which produce greater amounts of sperm and eggs (Sastry, 1966) thus improving spawning success. Beginning in May, the second year nub adults and second year classic adults have more rapid gonad development than the younger classic adult scallops. Nub adult scallops and second year classic adult scallops are the first to spawn in June, which produce the classic seed scallop.

First year classic adult scallops (12 months) may also spawn in June if environmental conditions (phytoplankton quality and quantity) are favorable for gonad development. When environmental conditions are adverse, gonad development in first year classic adult scallops is retarded and spawning cannot take place until the fall temperature change producing a late set of scallops or nub scallops. Observations made in Nantucket Harbor (Curley, 2003) document the classic adult scallop has been spawning later in the summer due to variations in water temperature and fluctuations in phytoplankton species and abundance.

Nub scallops were found to spawn for the first time after their second winter at 21-22 months of age. This spawn is suggested to be viable due to the age, the size of eggs in the larger gonad and health of the surviving nub scallops. Because the second year nub scallops reproduce in June, nub scallops greatly contribute to the population of scallops in the harbor. The classic scallop represents the stability of the reproductive success of the bay scallop population in Nantucket Harbor. To ensure the production of the classic scallop, the nub scallops need to be protected from harvest until they have spawned in June.

Massachusetts General Law, Chapter 130 section 70 defines a legally harvestable bay scallop as one with a well-defined raised growth line. Nub scallops that are only 13 months old can be legally harvested with a raised growth line, even though they have not yet spawned for the first time. The intent of this law, however, was to ensure that all bay scallops reach sexual maturity and spawn before they can be harvested. While the harvesting of nubs may be legal under state law, it is contrary to the intent of the Massachusetts General Law. Since the identification of a well-defined raised growth line can be quite subjective, Shellfish Wardens have some latitude in the interpretation of Massachusetts General Law (Ch. 130 sec. 70). The nub growth line, close to the umbo, is a raised growth line but not always well-defined. Local towns could nevertheless adopt a "no nub" harvest rule as the Town of Nantucket did in the years of 2000 and 2001.

In this experiment, 59.5 % of the nub adult scallops survived to the post-spawning period and reached 23 months of age. As maturation of sperm and eggs take approximately 60 days (Sastry, 1971), nub scallops can regenerate their gonads over the summer and spawn a second time in the same year during the fall if environmental conditions are favorable. In cage 2, several nub adult scallops appeared to have spawned again in the fall based on color and condition of the gonad. These successive spawning events add a great deal of productivity to the biomass, and may provide the best opportunity to create a sustainable fishery.

During some years, the second year classic adult and second year nub adults are the only age classes to spawn during the first spawning event in June. Commercial scallop fishermen selection may accelerate the shift from the majority of scallops being the "classic" to the majority being the "nub" scallop. Since the 21 to 22 months old nub adult scallop produces the classic adult scallop, the removal of the nub adult scallops prior to spawning causes a shift in reproductive output. If the majority of second year classic and nub adults are removed through harvest and environmental conditions are not favorable for the first year classic adults to spawn, it is possible for there to be some years when there is no June spawn.

Environmental conditions, fishermen selection and other spawning irregularities all contribute to large fluctuations in bay scallop populations from year to year. As environmental degradation increases, it is critically important to protect all pre-spawn age classes of scallops. Protecting the nub adult scallop long enough for it to spawn promotes good diversity in age classes and strengthens the population's ability to rebound from poor spawning events.

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FIGURE CAPTIONS

Figure 1. Water Temperature Trend for Nantucket Harbor (2001). Spawning occurs when there is a rapid rise of fall in water temperature from 20 C – 22.2 ^{o}C.

Figure 2. Nantucket Bay Scallop Growth and Spawning Trends for Two Age Cohorts, Classic Scallops (Diamonds) and Nub Scallops (Squares).

Figure 3. Map of Nantucket Harbor showing location of cage placements.

Figure 4. Mortality of Experimental Scallops Between Each Visit as Shown as % of Total.

Figure 5. Number of Surviving Nub Scallops in Cages 2, 3, and 4.

Figure 1

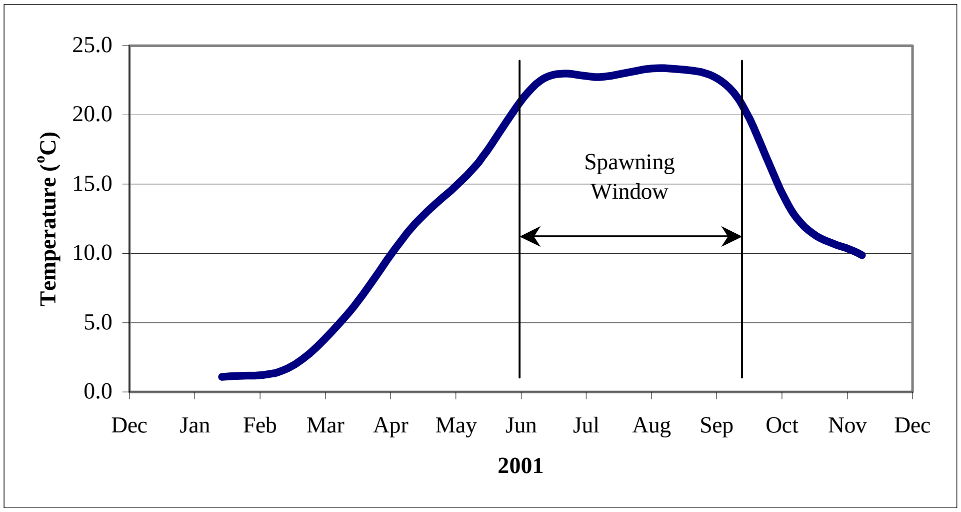


Figure 2.

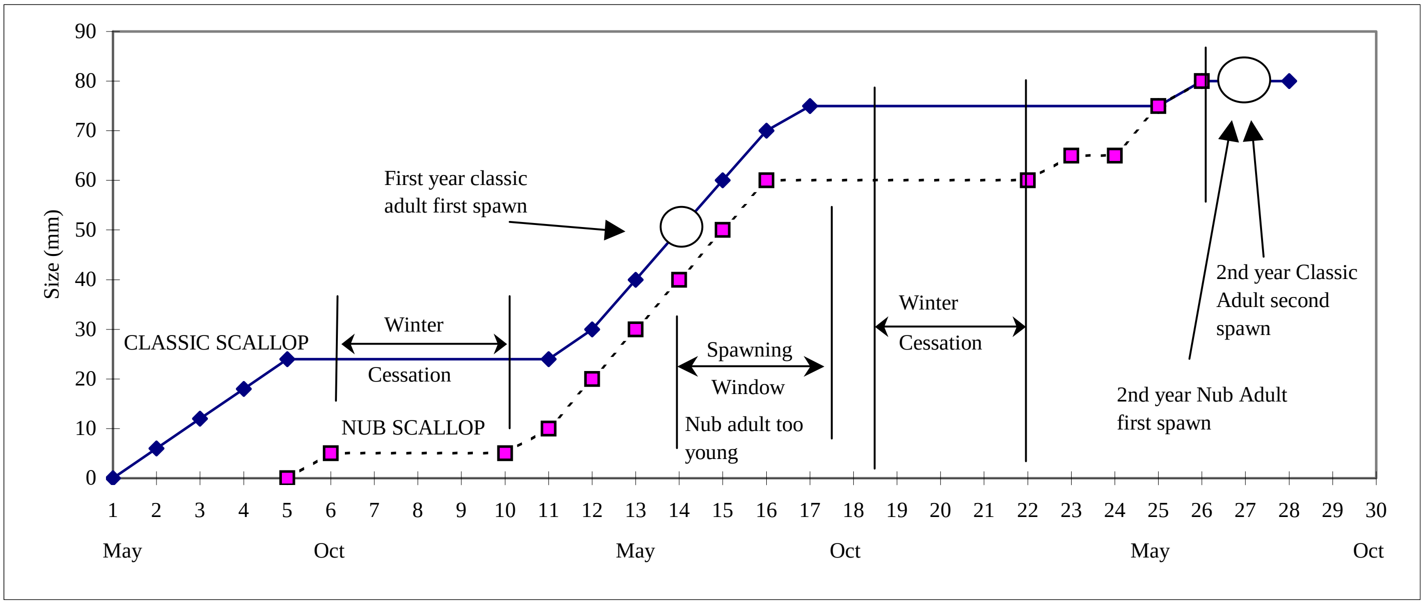
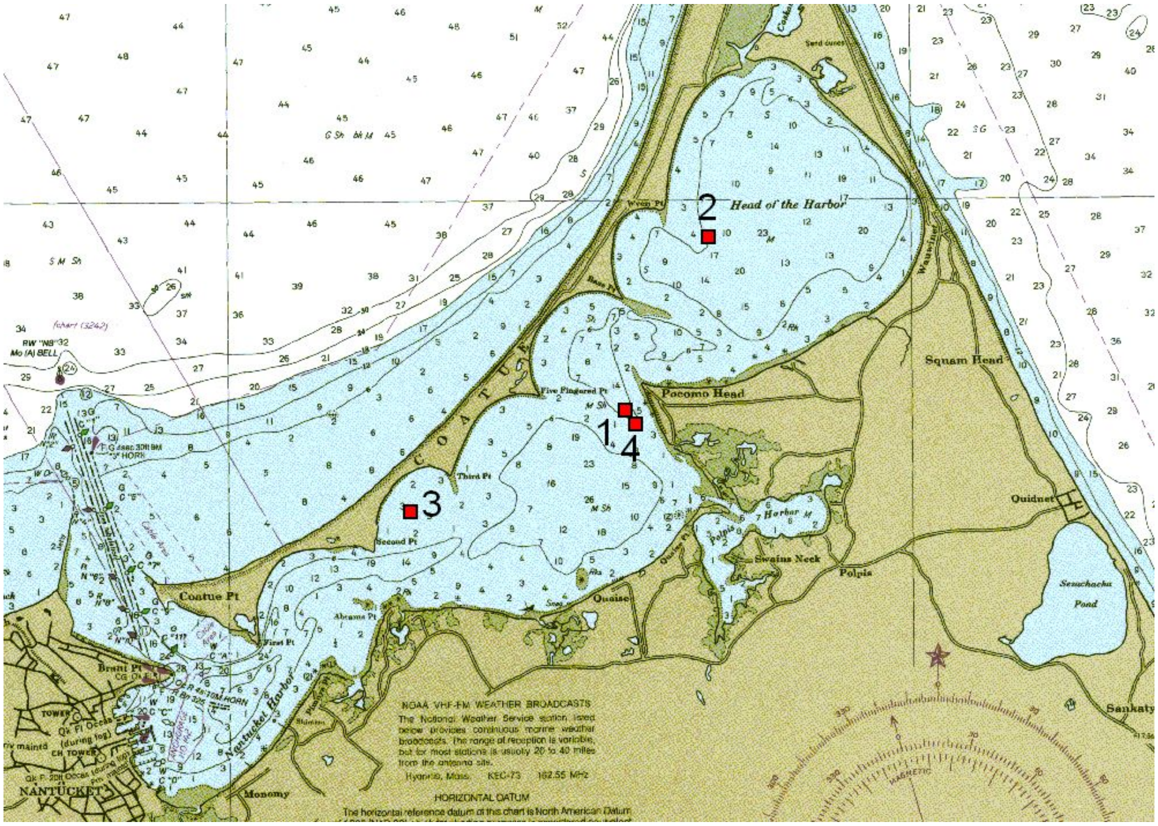


Figure 3.



1
2
3
4
Head of the Harbor
Pocomo Head
Squam Head
Quidnet
Polpis
Swains Neck
Coatue Pt
Five Fingered Pt
Third Pt
Second Pt
First Pt
Quaise
Sankaty
NANTUCKET
Nantucket Harbor
Monomy
NOAA VHF-FM WEATHER BROADCASTS
HORIZONTAL DATUM

Figure 4.

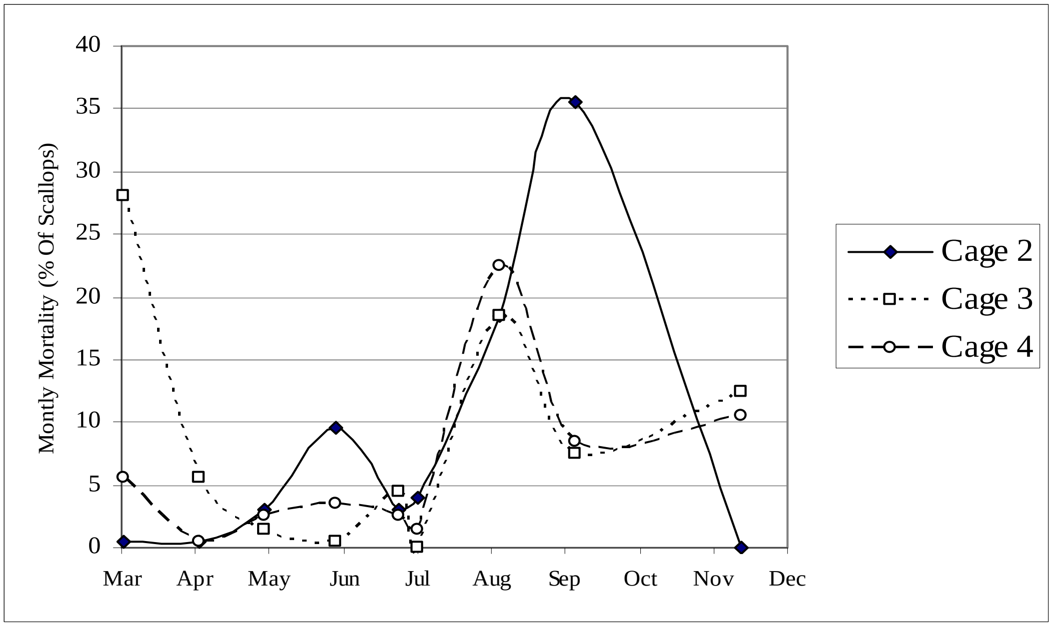


Figure 5.

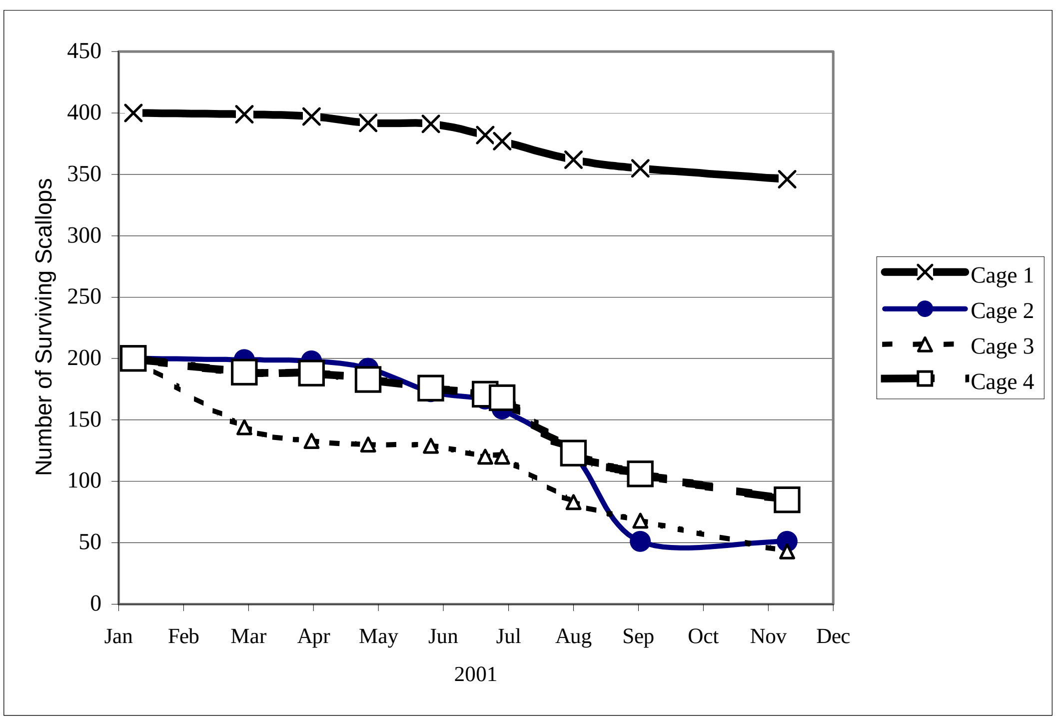


TABLE 1. Survival rates of bay scallops, pre-spawn, post-spawn, harvest.

TABLE 2. Gonadal stage data for caged scallops in 2001.

TABLE 1.

Survival Rates of scallops, pre-spawn, post-spawn, harvest

	pre-spawn	post-spawn	harvest
cage 1	90.50%	88.70%	86.50%
cage 2	79.50%	61%	23.50%
cage 3	60%	43.50%	21.50%
cage 3*	80%	58%	28%
cage 4	84%	61.50%	41.50%

Cage 3* survival rate based on 150 animals

TABLE 2.

Sampling date	Control	Nub Cage 2	Nub Cage 3	Nub Cage 4
3/2/01	1	ND	ND	ND
4/31/01	1	2	2	3
5/30/01	1	3	3	3
6/25/01	2	3	ND	4
7/3/01	3	4	4	4
8/6/01	4	5,6 & 7	5 & 6	5
9/12/01	5 & 6	7	ND	ND
11/16/01	ND	ND	5	7
12/4/01	7	ND	ND	ND